Space-Time Dynamics of Soil Moisture and Temperature - Scale Issues

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Project Summary

Soil moisture and temperature are the two key state variables determining the combined water and energy balances of the land surface and the atmosphere. Unfortunately, the problem of accurately estimating soil moisture and temperature over field-, watershed-, regional-, and global- scales is complicated by the overwhelming heterogeneity of the soil environment and the highly non-linear nature of mass and energy fluxes. An improved, quantitative understanding of the dynamics of soil moisture and temperature, and their role in the interaction between the land surface and the atmosphere, requires a careful integration of soil moisture and temperature measurements with detailed characterization of the physical, hydraulic, and thermal properties of the soil medium.

A large number of remote sensing techniques (e.g., passive microwave, gamma ray, and multispectral radiometers) to obtain large-scale soil water content and heat flux measurements at the soil surface, and *in-situ* measurement techniques (e.g., time or frequency domain reflectometry, neutron probe and thermocouple procedures) to obtain point-scale soil moisture content and soil temperature measurements have been developed during the past few decades. As these techniques evolve, optimal analysis, aggregation, and assimilation of observed data associated with different area or volume supports (and made from different platforms) becomes the most critical step. Many researchers have recognized the critical role of soil moisture and tried to develop models which extend the point-scale or local-scale physics of soil hydrology to the larger domains of mesoscale meteorological and global circulation models. These models require pixel-scale information about the physical, hydraulic and thermal characteristics of the soil in order to properly simulate soil hydrologic processes as part of the combined energy and water balances between the land surface and the atmosphere.

Actual measurement of soil moisture, soil temperature, and soil properties at different supports is expensive, and often impractical. We propose a simpler indirect soil moisture estimation method using soil, landscape, vegetation, and precipitation information. Establishing a generic approach of this type requires information from several field experiments conducted at different space and time scales under different environmental conditions (soil, landscape, vegetation, climate), followed by adaptive spatio-temporal data analysis and aggregation. The Southern Great Plains Hydrology Experiment 1997 (SGP97) database provides an excellent basis for this kind of study. A soil property characterization team led by PI Mohanty participated in the SGP97 field campaign. A large number of soil cores were taken over quarter sections in each of the three intensively monitored research areas (Central Facility, El Reno, and Little Washita) (Figure 1) within the SGP region. Sampling was based on *a-priori* information and concurrent inspection of different representative soil, landscape, and vegetation combinations. In addition to direct subsurface (0~1 m) soil moisture and temperature measurements, 160 soil cores were used to characterize the soil physical (texture, bulk density, and organic matter content), hydraulic (water retention and hydraulic conductivity functions, including hysteresis and temperature effects) and thermal (volumetric heat capacity, heat diffusivity, and thermal conductivity) properties. A complete list of soil properties and the invoked measurement methods is given below:

	Soil Property	Method
1.	Soil texture	18-point particle size analysis

2.	Organic carbon	Analytical
3.	Bulk density	Standard approach
4.	Soil structure and color	Visual examination and Munsell soil chart
5.	Saturated hydraulic conductivity	Constant head permeameter (CHP)
6.	Saturated hydraulic conductivity, $f(T)$	CHP, varying room temperature in increments
7.	Soil water retention	Tempe cell + Pressure plate (multistep outflow)
8.	Soil water retention, $f(T)$	Tempe cell; varying the room temperature
9.	Soil water retention, hysteresis	Tempe cell; repetitive drainage and imbibition
10.	Volumetric heat capacity	Dual probe heat pulse
11.	Heat diffusivity	Dual probe heat pulse
12.	Thermal conductivity	Dual probe heat pulse

The SGP97 soil characterization effort has yielded a very unique set of data for deriving important soil, topographic, and vegetation parameters. The proposed work will establish neural-network-based pedo-topo-vegetation transfer functions (PTVTFs) describing soil hydraulic/thermal properties and soil moisture/temperature at different (hierarchical) spatial scales. Following successful development and testing of the PTVTFs in the SGP97 region, aggregated soil parameters will be derived using new GIS-based rules/templates and scaling schemes. Operational success of the aggregated soil parameters will be tested for water and heat transport to the deeper soil layers, by comparing numerical simulation results against the measured data. Additionally, a unique high quality digital database of soil physical, hydraulic, and thermal characteristics including the pixel-scale parameters for the SGP97 study area will be created for a wide range of applications, including soil-vegetation-atmosphere transfer (SVAT) modeling, hydrologic modeling, subsurface flow/transport modeling, land surface water/heat flux balance calculations, data assimilation studies, calibration of remote sensing data, and others. Specific goals are to:

Develop pedo-topo-vegetation transfer functions (PTVTFs) that predict the hydraulic and thermal properties of large land areas from readily available soil taxonomy (e.g., soil type, texture, porosity, bulk density), landscape (e.g., slope, aspect, elevation, depth to water table), and land use/cover (e.g., vegetation type, vegetation density, rooting depth, tillage/management practice) parameters at different scales.

Identify the soil, landscape, and vegetation factors that are the most important for establishing PTVTFs using neural network (NN) analysis.

Quantify the observed spatio-temporal structure of soil moisture, soil temperature, and related soil, landscape, and vegetation factors using GIS-adaptive data analysis techniques.

Using thePTVTFs and observed spatio-temporal structures, **develop** a GIS-compatible upscaling scheme that relates point measurement of hydraulic and thermal properties of soils in the vadose zone to the effective or aggregated properties of larger land areas. **Investigate** the effectiveness of using aggregated soil parameters to simulate water and heat transport to deeper depths for a mosaic of one-dimensional soil pedons (for relatively flat land surfaces), and **compare** model simulations with measured moisture and temperature profiles.

Research Methods

Task 1: Database Development

Multistep outflow and soil water retention data will be used to determine the hydraulic functions using our in-house inverse models HYDRUS-1D and RETC. Similarly, soil thermal gradient data using the dual probe heat pulse method will be analyzed for thermal properties with the LINEPARM and HPC (inverse) models.

In order to accomplish the objectives of this proposal, and to provide complete, high- quality reference data for other users of the SGP97 soil database, the physical, hydraulic, and thermal characteristic information will be integrated into a spatial information framework which will associate the soil core sample locations, the derived hydraulic and thermal characteristics, and associated site information, into a geographically-referenced (GIS) framework for the LW, ER, and CF study areas (Figure 1). The GIS data sets will be freely available to other researchers over a [World Wide Web server](#).

Task 2: Development of PTVTFs using Neural Network Analysis

Using the SGP97 soil characteristics database developed in Task 1, a neural network/ bootstrapping analysis will be conducted on part of the data set to develop pedo-topo-vegetation transfer functions (PTVTFs), and their uncertainty, relating output data (soil hydraulic properties, soil moisture content, soil temperature) to input data (soil type, texture, bulk density, slope, aspect, elevation, vegetation type, vegetation density, rooting depth). This approach is expected to yield an efficient alternative to expensive actual measurement of soil moisture content, and soil hydraulic/thermal properties, over large land areas using available (digital) maps and the GIS-based data aggregation and assimilation techniques described in Task 3.

Task 3: Spatio-Temporal Data Analysis, Aggregation, and Assimilation in GIS

Task 3 encompasses (i) the coupling of different components in a GIS-framework, (ii) spatio-temporal data analysis, and (iii) spatial-temporal data aggregation for deducing field- or pixel-scale variables/parameters. Figure 2 gives a overview of our proposed approach. Besides developing interface modules between individual components, we will develop adaptive space-time data analyses, aggregation, and assimilation modules currently not available in ARC/INFO, using the ARC Macro and AVENUE language. Based on the neural network and spatial data analysis, we will develop a series of GIS-based information processing rules/templates (e.g., Topography-Soil-Vegetation Index) for aggregating point-scale measurements to pixel-scale soil (physical, hydraulic and thermal) properties and state variables (e.g., soil moisture content). Among others, different scaling techniques based on geometric, dynamic, and kinematic similarity will be investigated to aggregate the point- measured soil properties. Also we will use the simpler techniques of sensitivity analysis and first order analysis for quantifying the propagation of uncertainty from input parameter (point measurements) to model output (aggregated properties). Value-of-Information analysis will also be evaluated for answering the questions concerning how much additional information is needed to improve the accuracy of predictions.

Task 4: Simulation Modeling and Testing

Following the estimation of field- and pixel-scale soil properties and state variables, the HYDRUS-1D model will be used to simulate water and heat transport to deeper depths in the vadose zone for different fields or pixels using the concept of mosaics of large soil pedons (Figure 2). Measured profile soil moisture and soil temperatures will be used as initial conditions, whereas transient precipitation or controlled water input events will be used as external forcing boundary conditions to the model. Model predictions will be evaluated quantitatively and qualitatively against measurements at deeper depths under different soil, topographic, landuse, and climatic conditions of SGP97 (Oklahoma). This information will be utilized as feedback to the SVAT schemes including (aggregated) parameter estimation.

Project Management

PI Mohanty will be in charge of the project. He will provide the broad guideline for the project and oversee the research approach undertaken by other researchers in the team. Co-I van Genuchten will provide expertise in soil physics, numerical modeling, and NN-based PTFs. Co-I Miller will lead the work on developing spatio-temporal data coverages, data analysis/aggregation/ assimilation schemes, and necessary information flow network modules (across different components of the proposed integrated system) on the pre-selected GIS platform.

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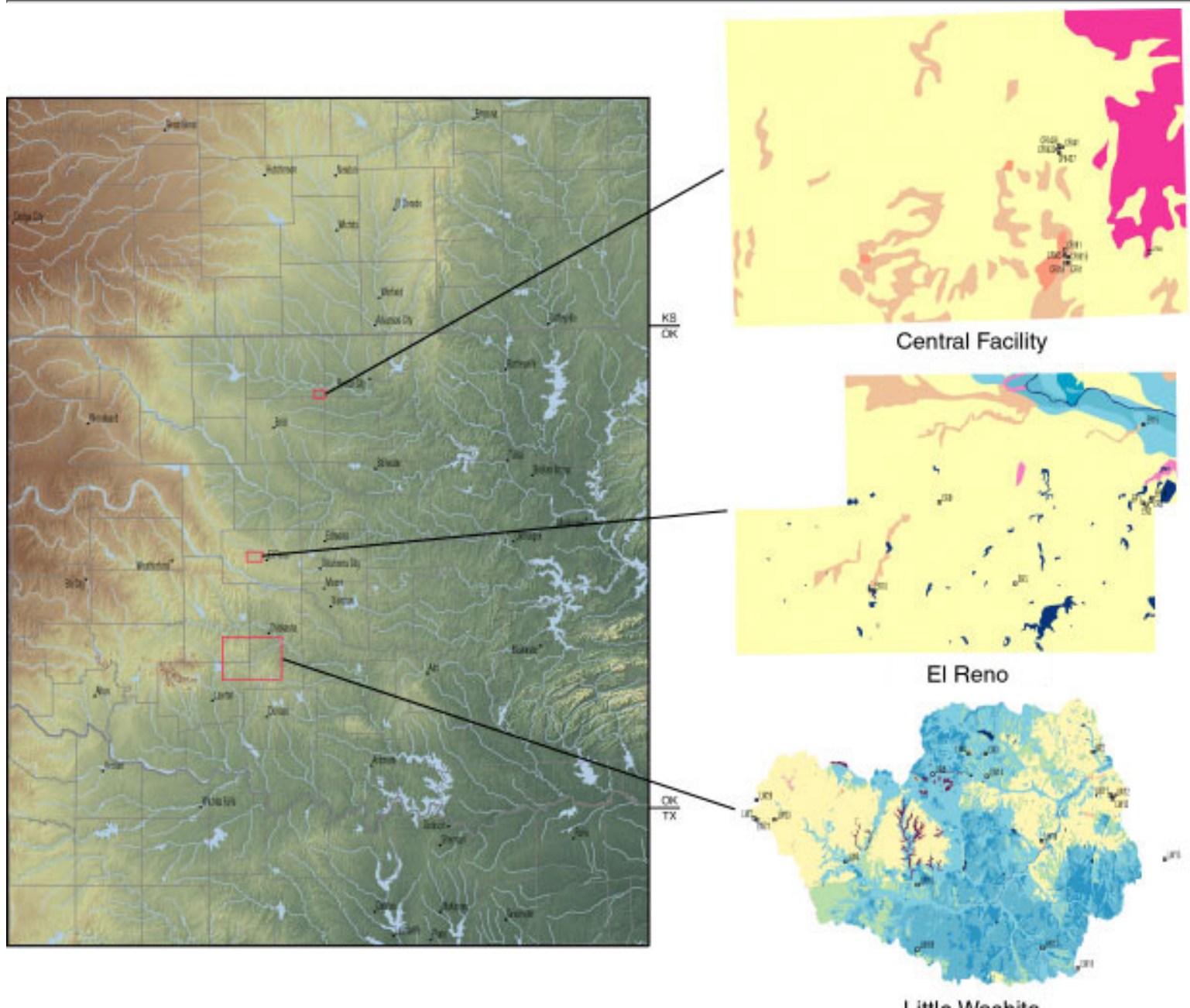Central Facility

El Reno

Little Washita

Figure1. Map of the SGP97 area and three intensive monitoring locations

Little Washita

USGS
Digital Topo Maps

SCS
Digital Soil Maps

Remote-Sensing
Digital Vegetation Maps

Data Analysis, Aggregation
Assimilation

Slope

Permeability

Type

Elevation

Bulk Density

Density

Aspect

Drainability

LAI

Layer 1

Layer 2

Layer n

Point Measurement
Soil Property

ARC/INFO Grid
GIS

Neural Network

Pedo-Topo-Veg Transfer Function
soil water content(h=0) = bulk density + elevation + LAI

ARC/INFO RDBMS
GIS

Soil Pedon

Neural Network

UNSODA

Texture

Structure

Organic Matter

K(h) and θ(h)

α   β   σ   Δh

P   ∇·∇   χ   λ

f(x)   ∫₀   HYDRUS   δ   ε

∂ᵘ $\frac{\partial T}{\partial t}$ ψ   ϑ

Black Box

Information Flow Using
Interface Module

Expert

ARC/INFO View/Plot
GIS

Output Moisture Content
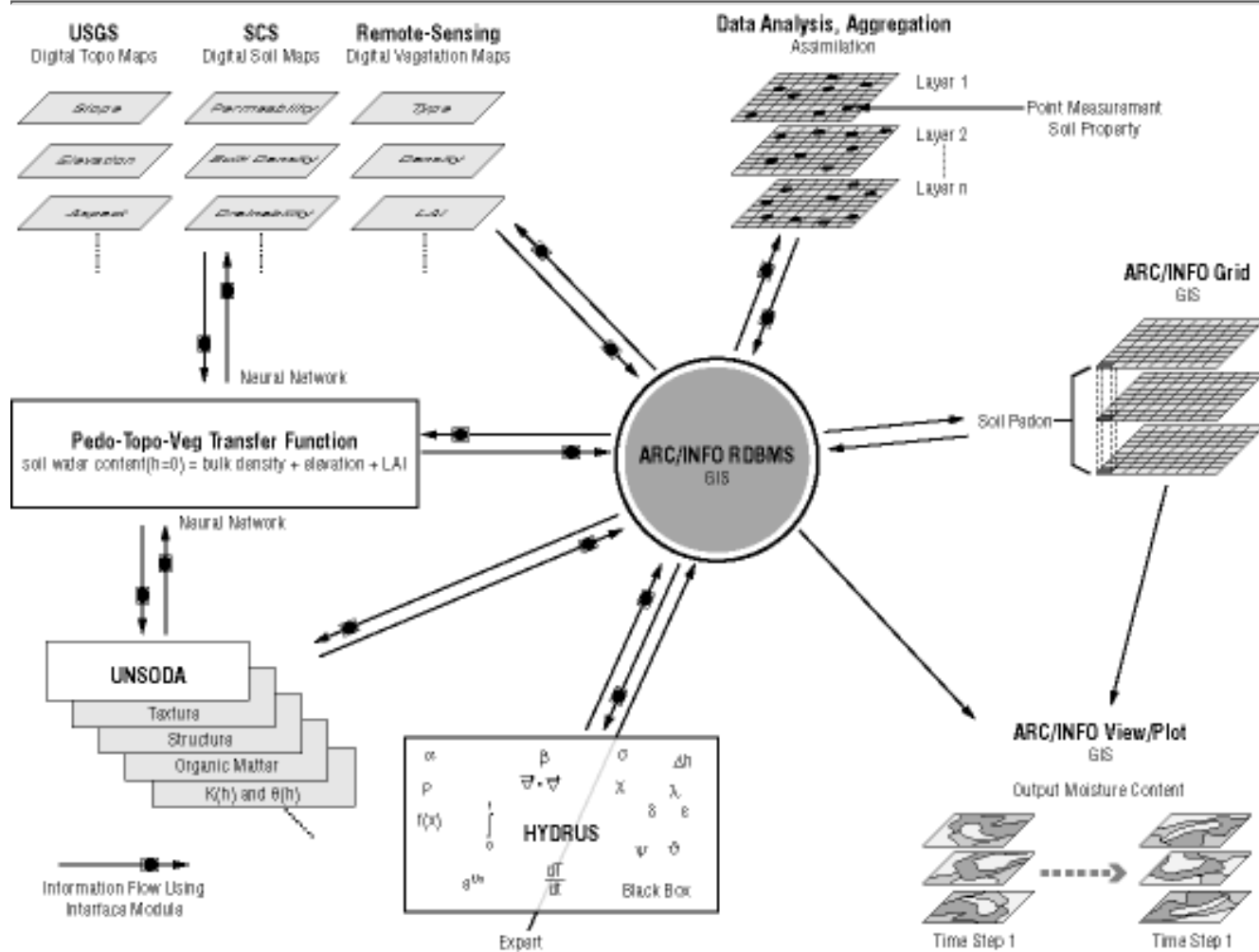
Time Step 1   Time Step 1

Figure 2. Information flow network for the integrated system

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